KASI LSST meeting (2016/04/25)

Cosmic Microwave Background Temperature Anisotropy from the Kinetic Sunyaev-Zel'dovich Effect

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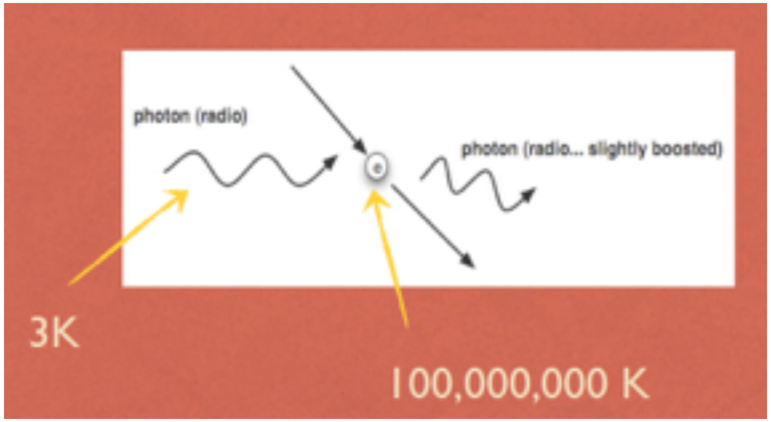
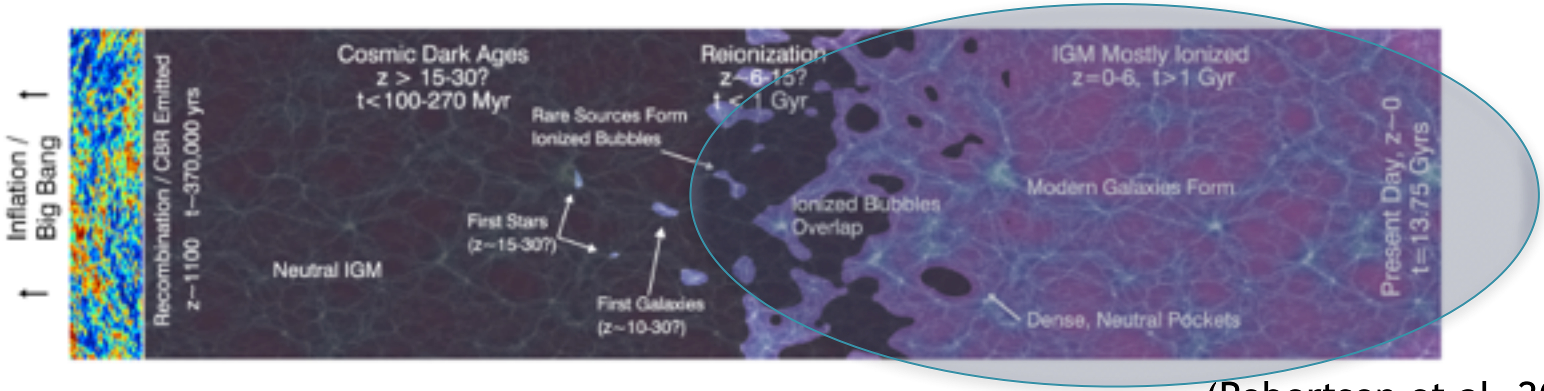
Garrelt Mellema (U of Stockholm)

Sunyaev-Zel'dovich (SZ) Effect

Change of temperature due to
interaction between CMB photons and free electrons…



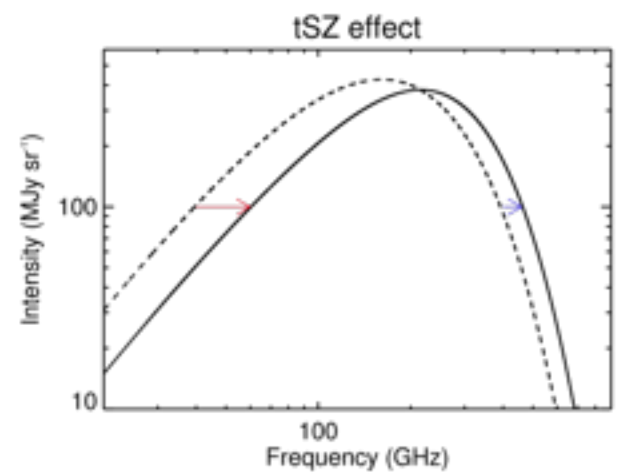
… produced by astrophysical sources in the post-Recombination era.



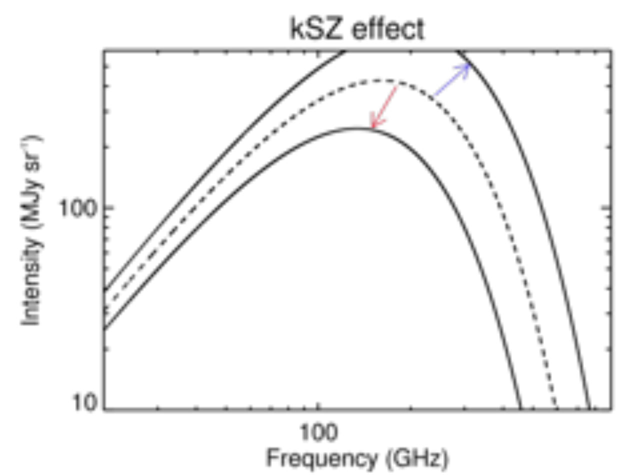
(Robertson et al. 2010)

Sunyaev-Zel'dovich (SZ) Effect

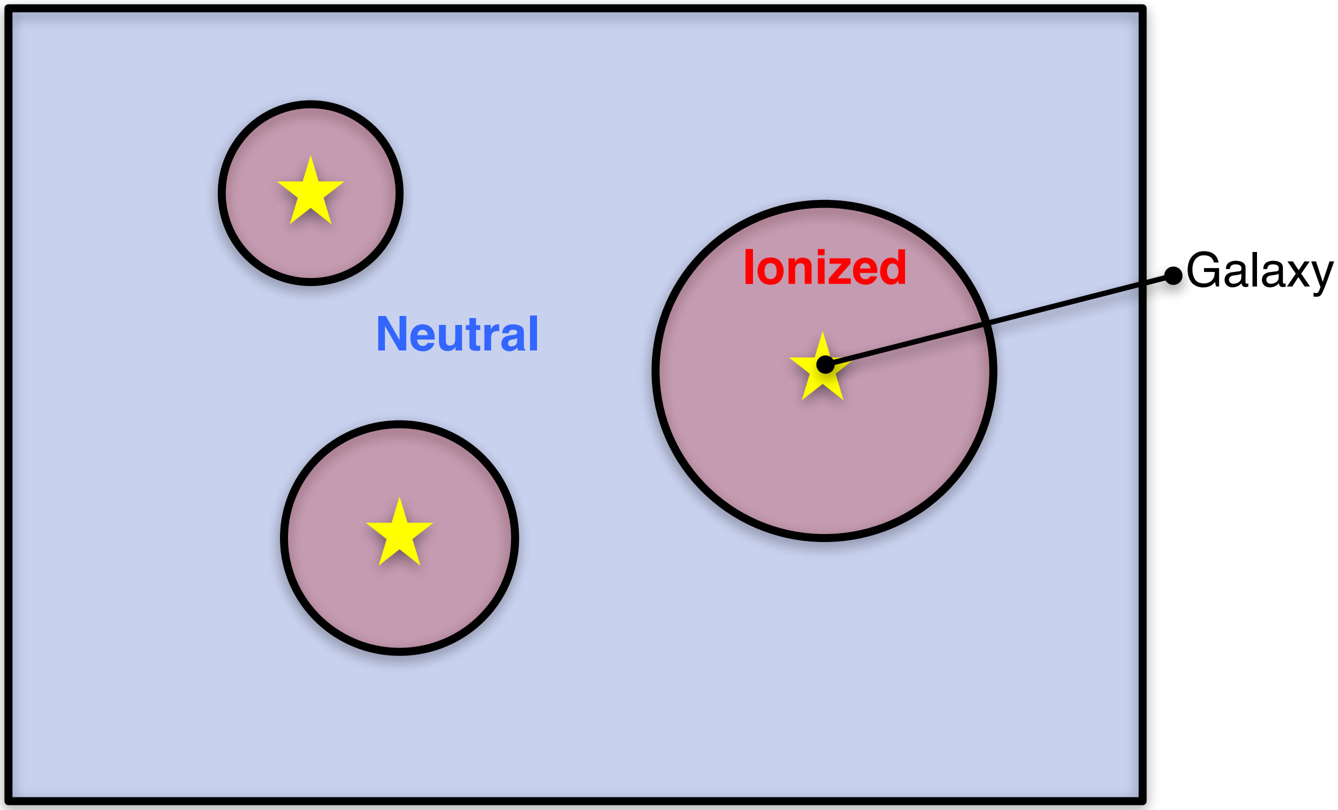
- Thermal SZ Effect (tSZ)
  Low energy photons up-scattered to have a higher frequency.



- Kinetic SZ Effect (kSZ)
  Doppler-shift by the bulk motion of the gas.

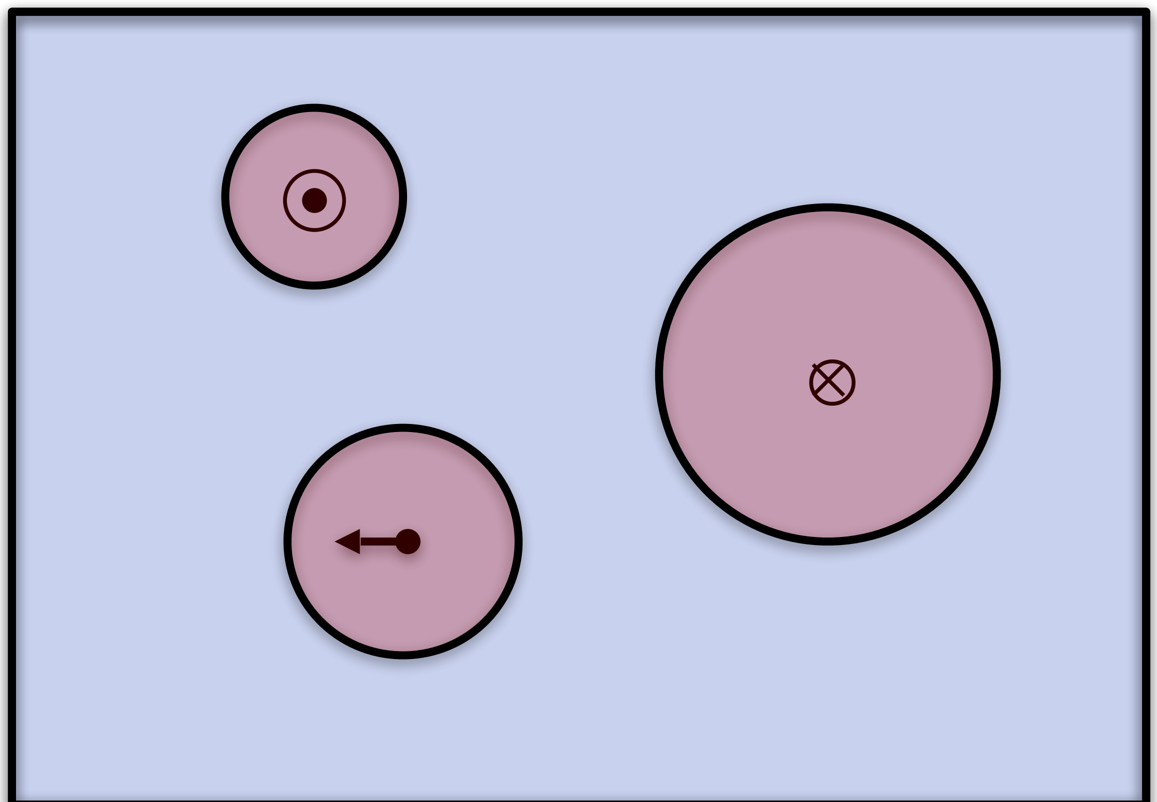


Kinetic Sunyaev-Zel'dovich Effect



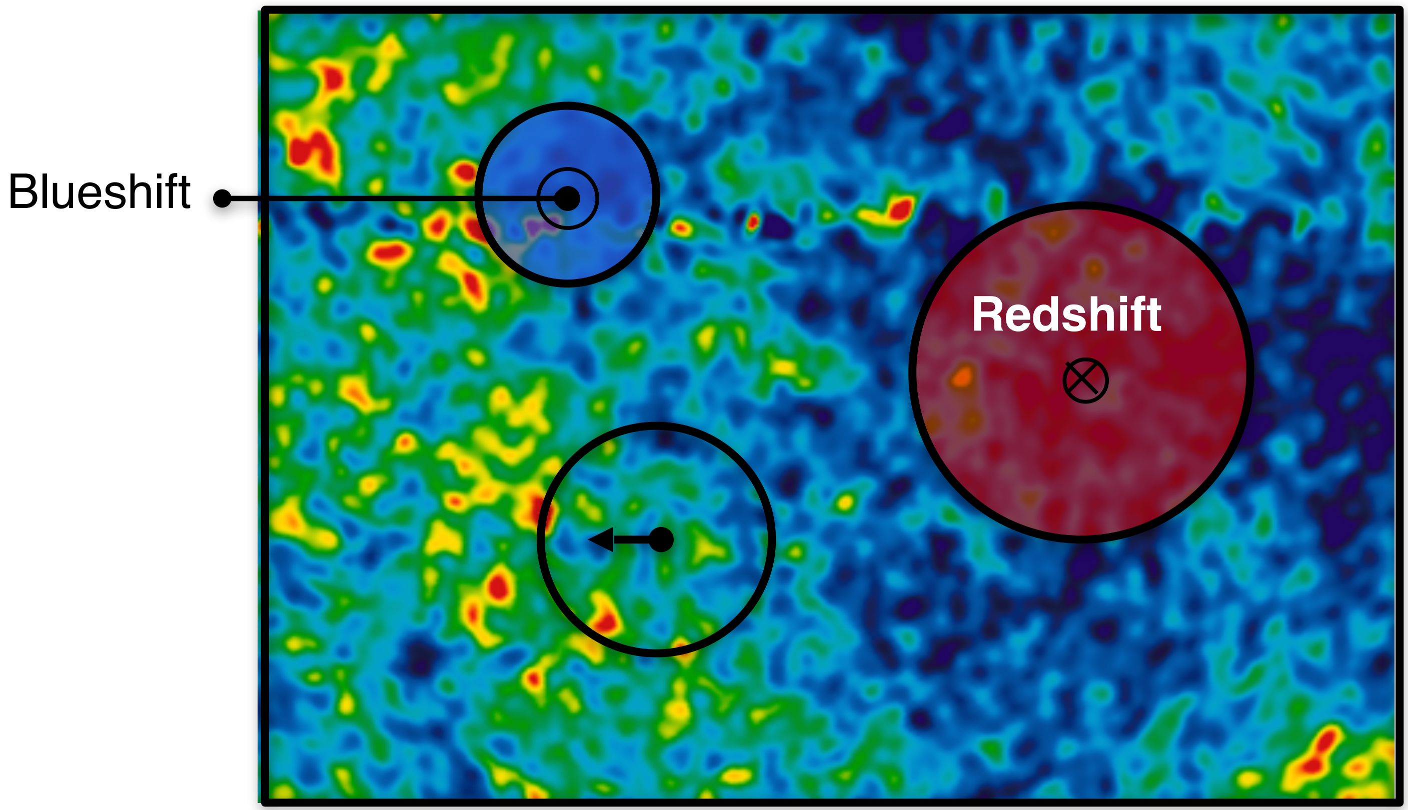
When the IGM has ionized parts, …

IGM during the EoR



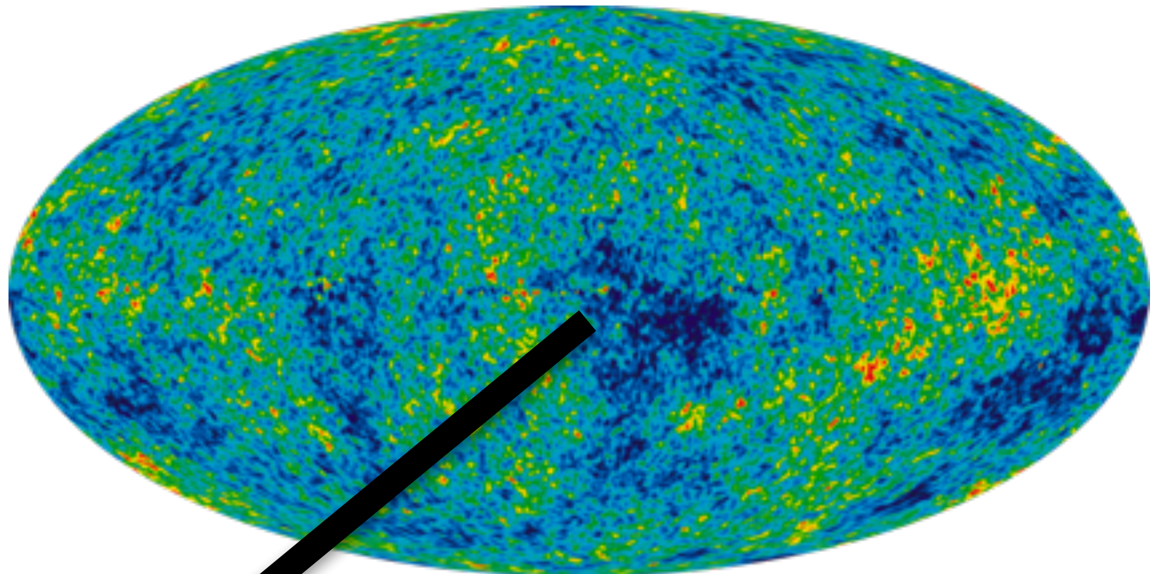
… each ionized patch can have different line-of-sight peculiar velocity.

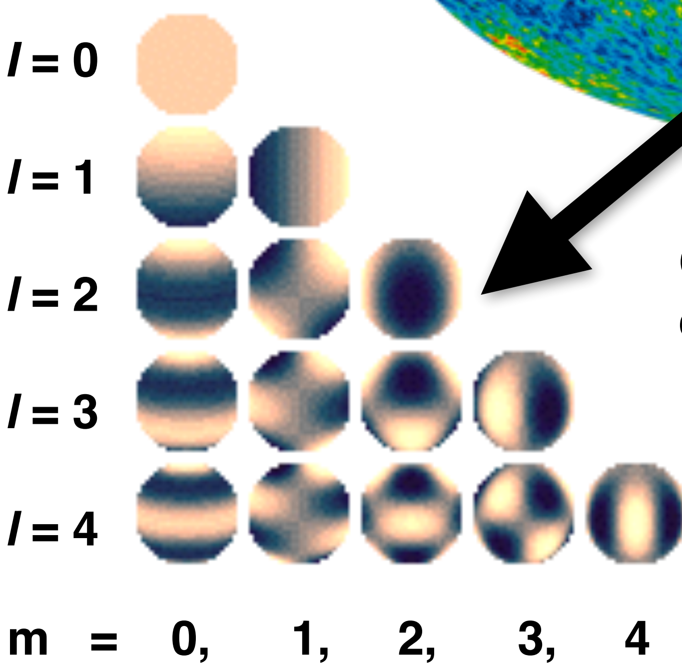
Kinetic Sunyaev-Zel'dovich Effect



The kSZ effect would red/blueshift the CMB according to the line-of-sight velocity of the ionized gas

CMB Power Spectrum



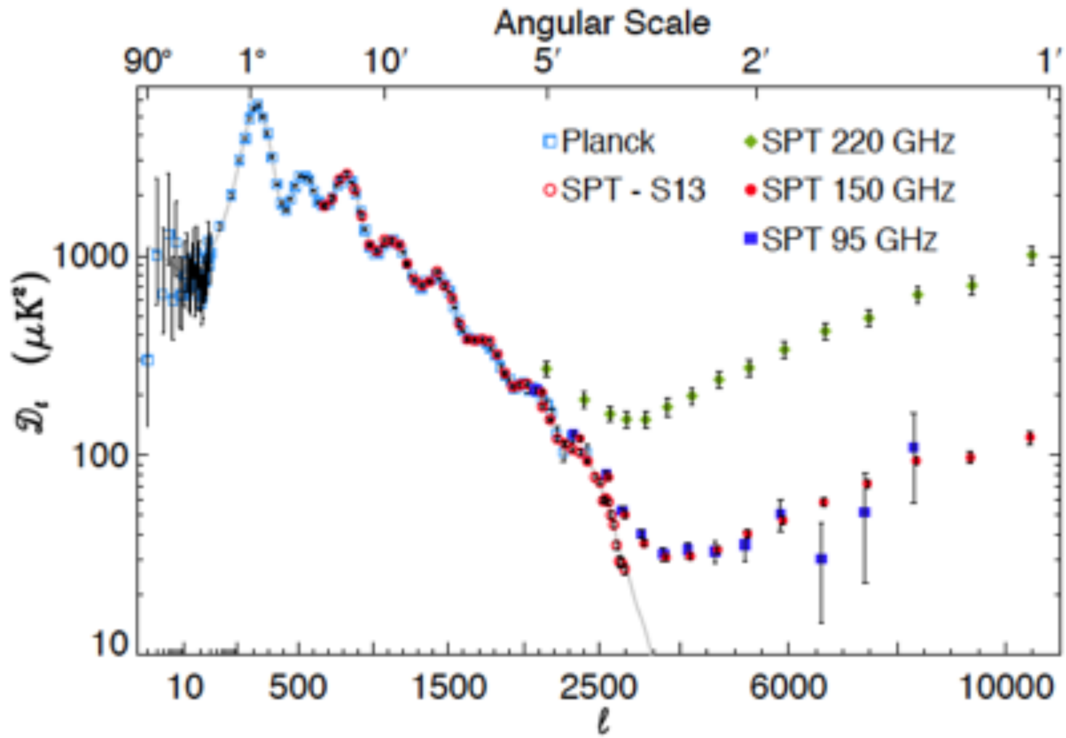


CMB temperature anisotropy can be decomposed into spherical harmonics.

$$a_{\ell m} \equiv \int d^2\hat{\gamma} Y_\ell^{m*}(\gamma) \frac{\Delta T}{T}(\hat{\gamma})$$

$$C_\ell = (2\ell + 1)^{-1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

CMB Power Spectrum from the South-Pole Telescope

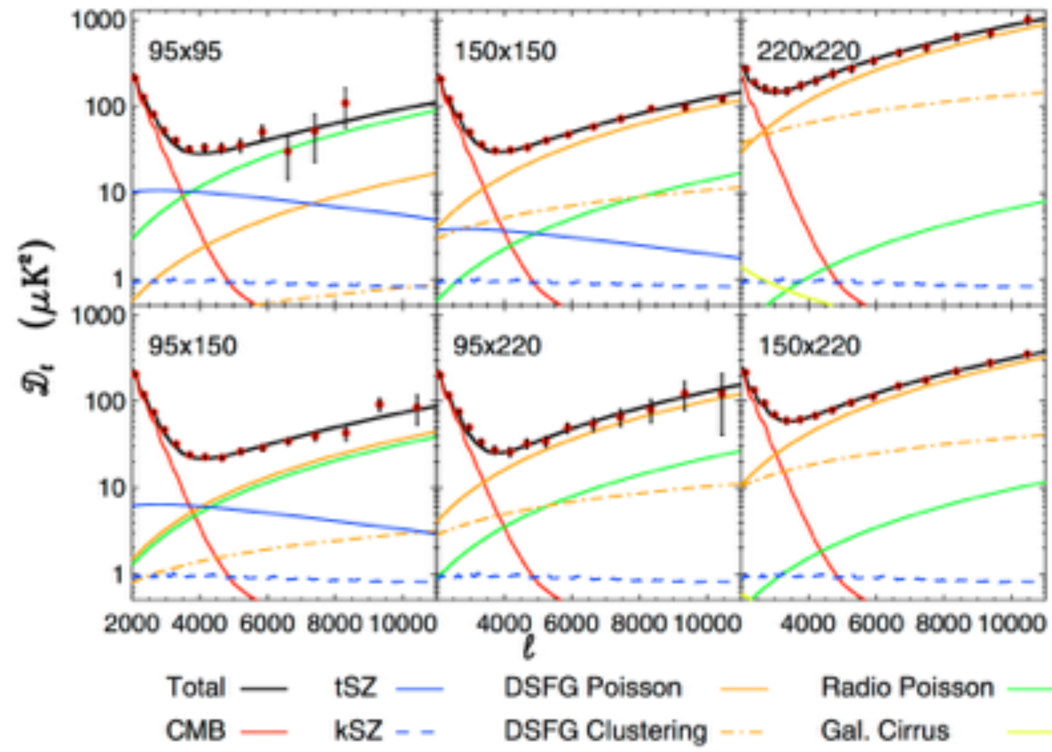


$$D_\ell \equiv (2\pi)^{-1}\ell(\ell+1)C_\ell$$

(George et al. 2015)

At *l* > 2000 or at angular scales below 5 arcmin, contribution from astrophysical sources dominate the signal.

CMB Power Spectrum from the South-Pole Telescope



$$D_{\ell=3000}^{\mathrm{kSZ}} = 2.9 \pm 1.3 \mu K^2$$ (George et al. 2015)

Using multi-frequency data, signals can be decomposed. For the kSZ effect, we only have rather a loose constraint at (*l* = 3000, 3 arcmin) at this point.

kSZ power spectrum

$$\frac{\Delta T}{T}(\hat{\gamma}) = \int d\tau \hat{\gamma} \cdot \frac{\mathbf{v}}{c}$$

$$\mathbf{q} \equiv X(1+\delta)\mathbf{v}$$

X: Ionized fraction

$$\frac{\Delta T}{T}(\hat{\gamma}) = \left(\frac{\bar{n}_{H,0}\sigma_T}{c}\right) \int \frac{ds}{a^2} (\mathbf{q} \cdot \hat{\gamma})$$

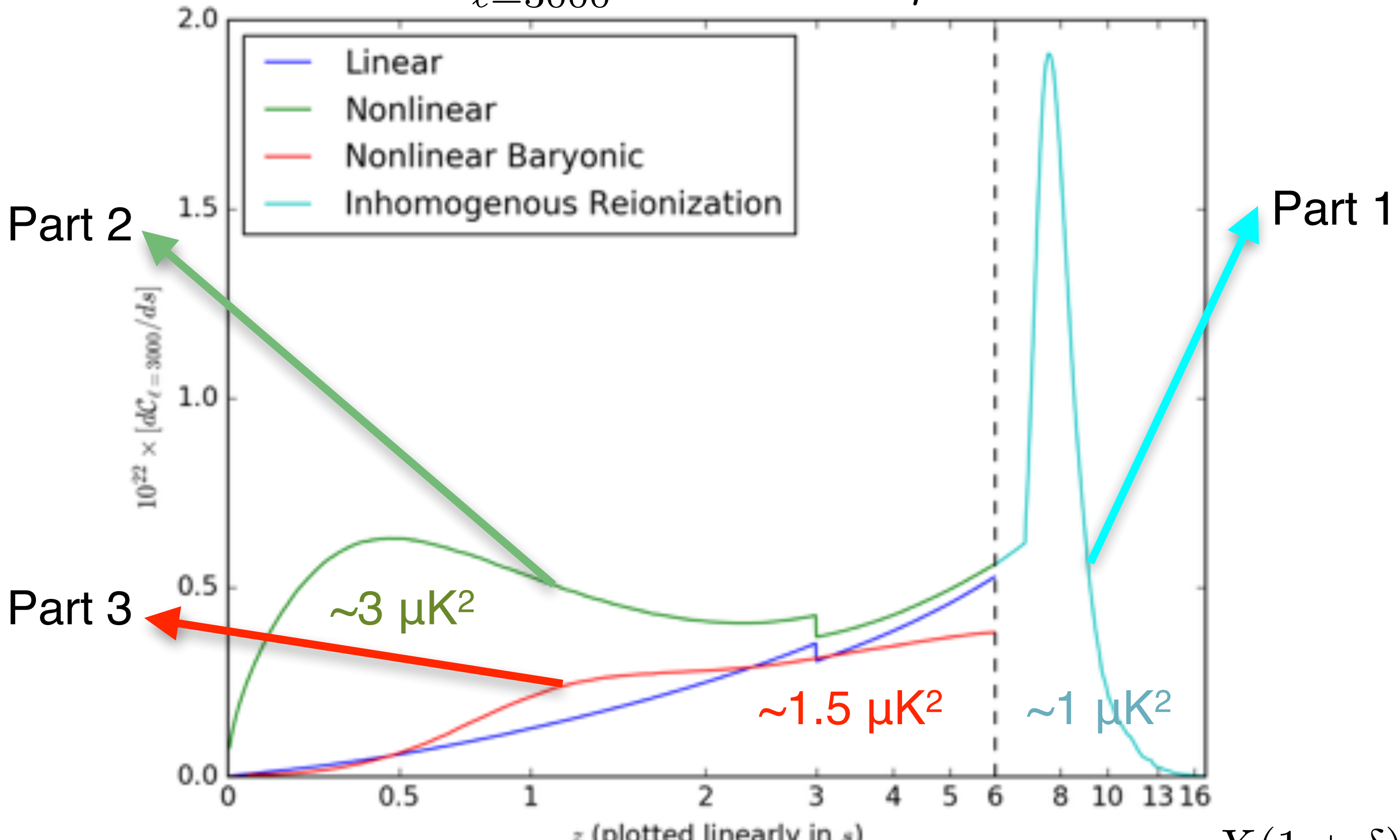
$$C_l = \left(\frac{\bar{n}_{H,0}\sigma_T}{c}\right)^2 \int \frac{ds}{s^2 a^4} \frac{P_{q_\perp}(k = l/s, z)}{2}$$

(See Park et al. 2013 for the derivation)

kSZ power spectrum is given by projecting the transverse component of ionized momentum field along the line-of-sight.

l = 3000 (3 arcmin) kSZ signal over the cosmic time

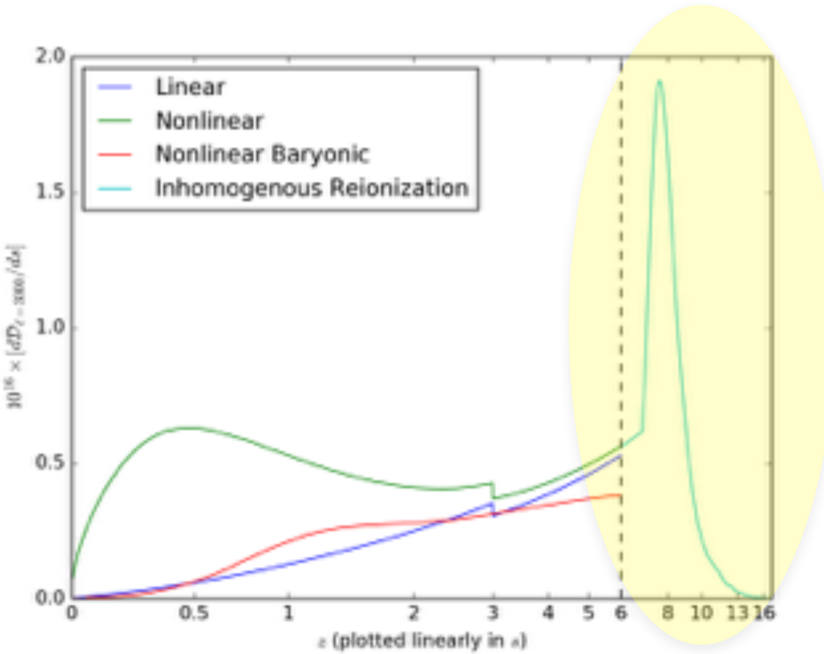
$$\mathcal{D}_{\ell=3000}^{\rm SPT} = 2.9 \pm 1.3\ \mu K^2$$

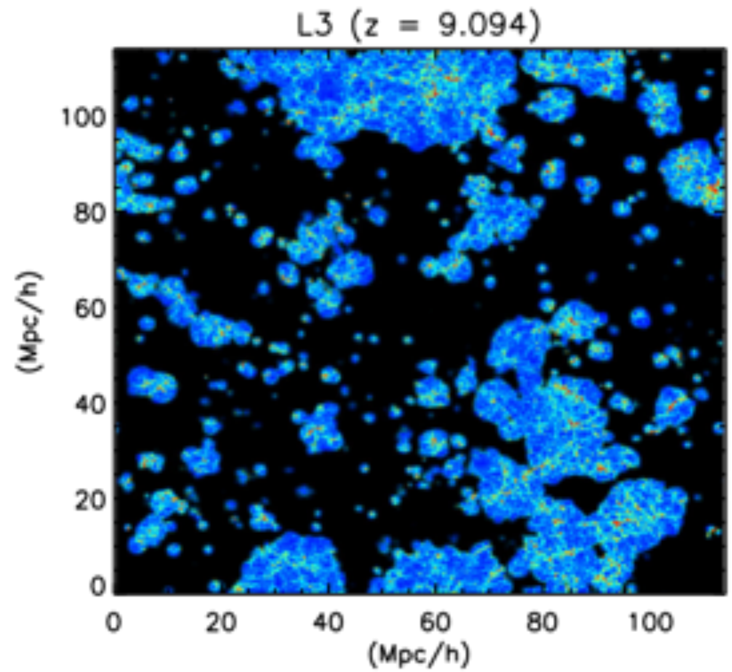


$$\mathbf{q} \equiv X(1+\delta)\mathbf{v}$$

1) **At $z > 6$, inhomogeneously ionized IGM gives a huge boost to the signal.**
2) **At $z < 6$, non-linear growth of structure and baryonic physics make huge impacts on the signal.**

Part 1) Reionization Signal





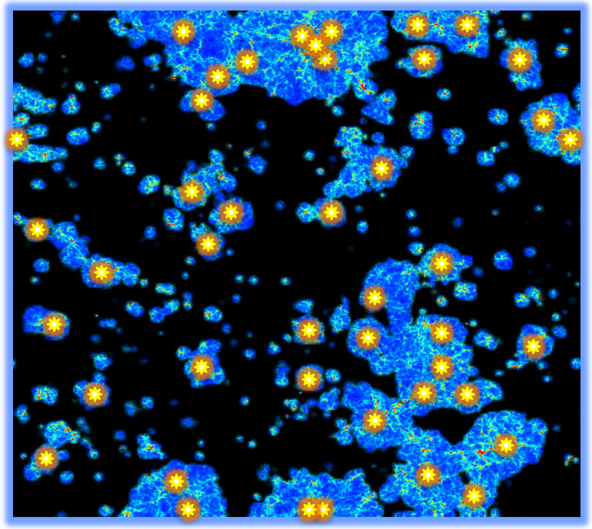
$$\mathbf{q} = X(1+\delta)\mathbf{v} = X(1+\delta_{lin})\mathbf{v}_{lin}$$

Density and velocity are in the linear regime whereas ionized fraction is highly fluctuating.

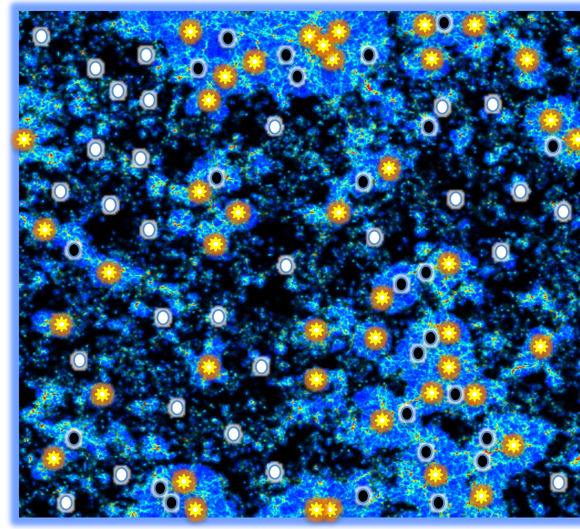
(Park et al. 2013)

Investigating the Impact of Low-mass Galaxies

High-mass sources only



Low-mass sources added

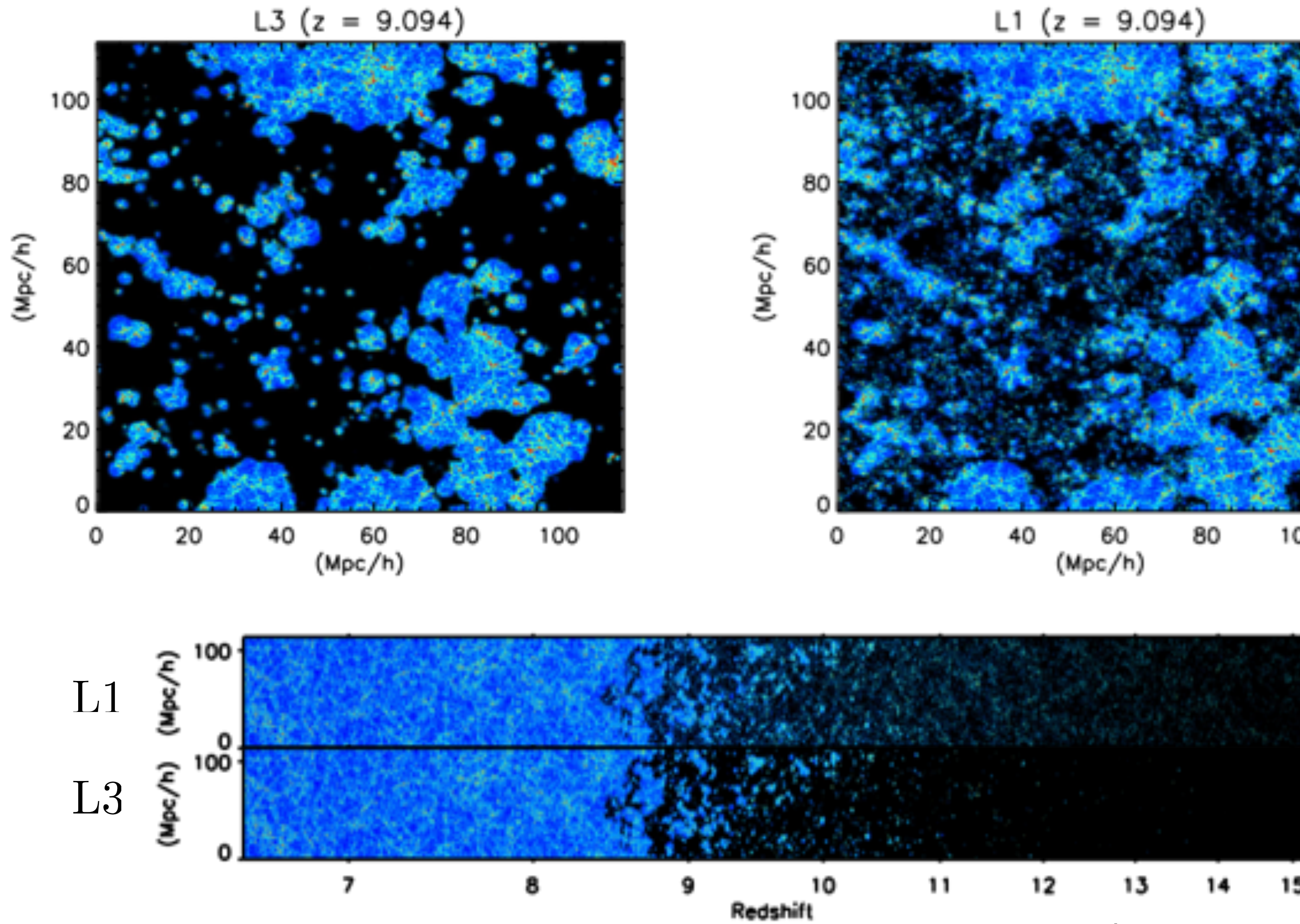


Low-mass galaxies stops forming stars early and, therefore, cannot create large ionized bubbles.

They create lots of tiny bubbles without changing the global ionization structure.

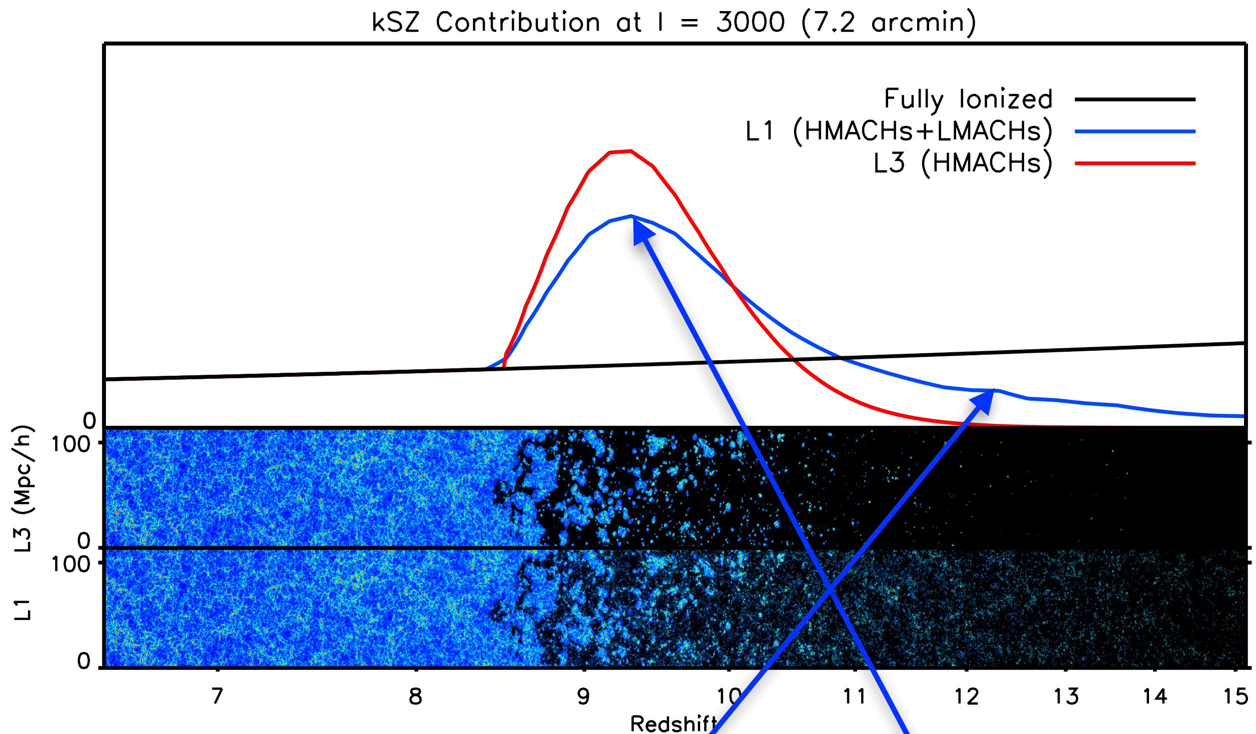
Reionization models with and without Low-mass Galaxies

High-mass sources only | **Low-mass sources added**



(Park et al. 2013)

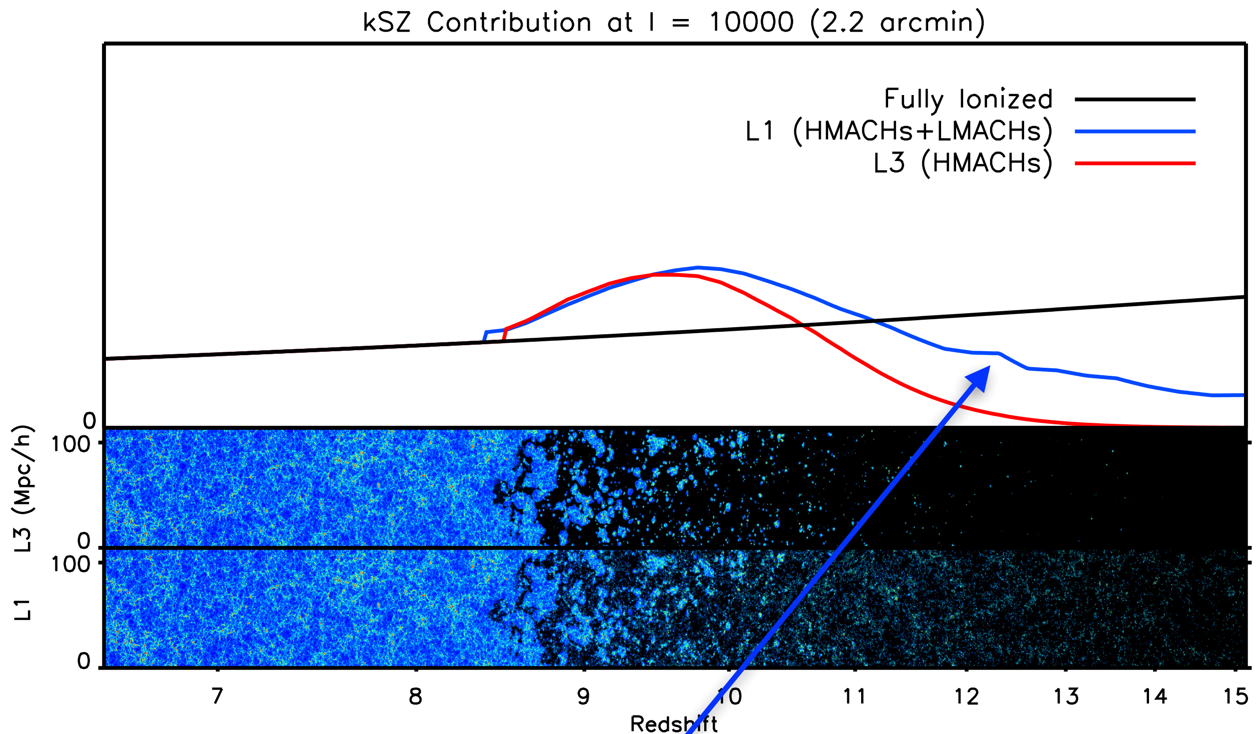
Reionization models with and without Low-mass Galaxies ($l = 3000$)



Including low-mass galaxies give a <u>lower signal at late time</u> and <u>higher signal at early time</u>. Both effects nearly cancel each other out to give a similar total signal, 0.9 μK^2.

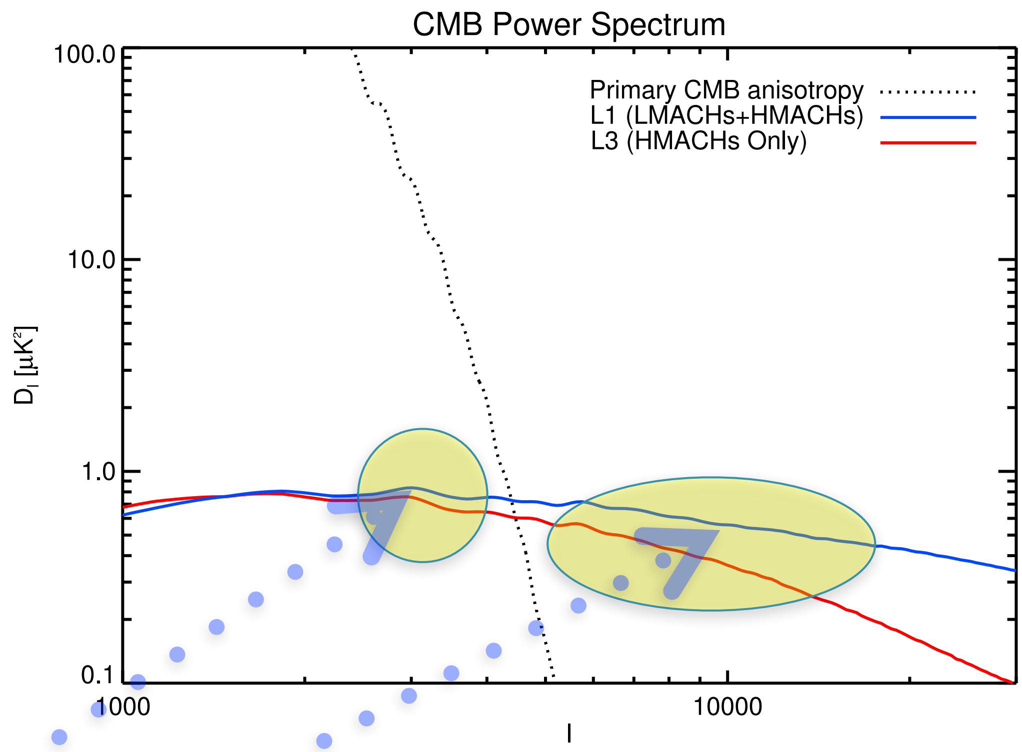
(Park et al. 2013)

Reionization models with and without Low-mass Galaxies (*l* = 10000)



The low-mass galaxies have a larger impact in smaller angular scales.

Result : Impact of low-mass galaxies on the kSZ Power Spectrum

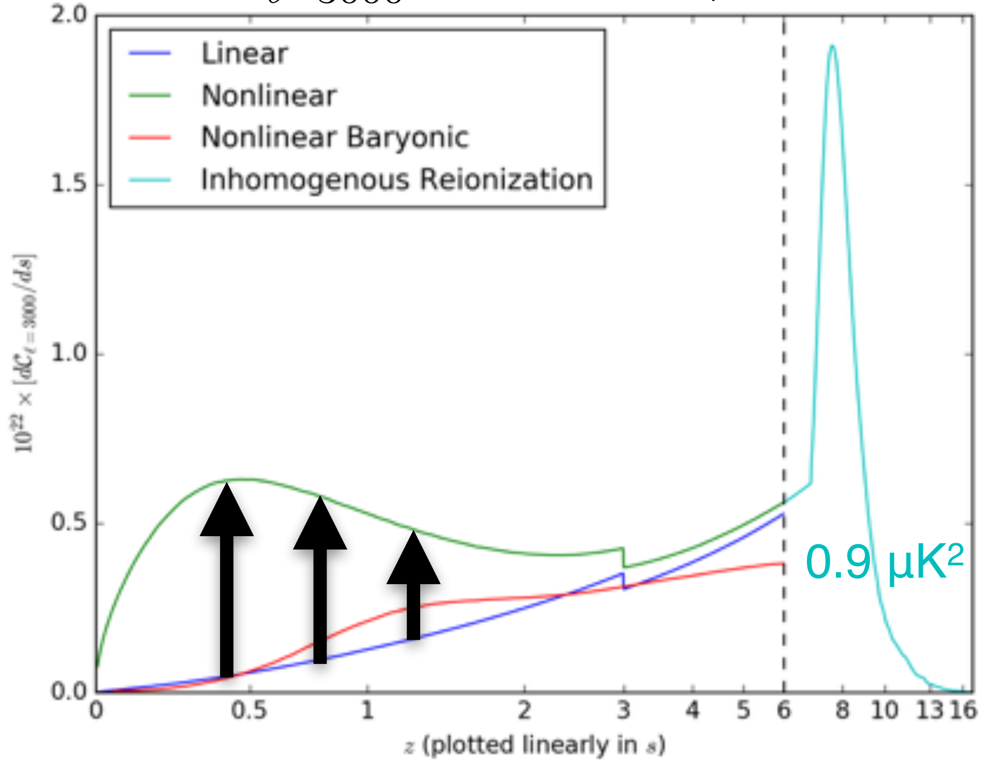


- **At *l* = 3000, adding low-mass galaxies make kSZ signal only 5% larger.**
- **At larger *l*'s, the difference is larger.**

(Park et al. 2013)

Part 2) Impact of Non-linear Growth of Structure in the Post-reionization Signal

$$\mathcal{D}_{\ell=3000}^{\mathrm{SPT}} = 2.9 \pm 1.3 \ \mu K^2$$



$$\mathbf{q} = X(1+\delta)\mathbf{v} = (1+\delta_{nl})\mathbf{v}_{nl}$$

Ionized fraction (X) is one everywhere. But, density (δ) and velocity (v) are in the nonlinear regime.

Expressing $P_{q,perp}$ in terms of density(δ) and velocity($\mathbf{v}$)

In the post-reionization epoch, IGM is fully ionized to a good approximation. Therefore, we can set X = 1.

$$\mathbf{q} = \mathbf{v}(1+\delta) = \mathbf{v} + \mathbf{v}\delta$$

$$\tilde{\mathbf{q}}(\mathbf{k}) = \tilde{\mathbf{v}}(\mathbf{k}) + \int \frac{d^3k'}{(2\pi)^3} \tilde{\mathbf{v}}(\mathbf{k}')\tilde{\delta}(\mathbf{k}-\mathbf{k}')$$

$$\tilde{\mathbf{q}}_\perp(\mathbf{k}) = \tilde{\mathbf{v}}_\perp(\mathbf{k}) + \left(\int \frac{d^3k'}{(2\pi)^3} \tilde{\mathbf{v}}(\mathbf{k}')\tilde{\delta}(\mathbf{k}-\mathbf{k}')\right)_\perp$$

Since the transverse mode is negligibly small for velocity, the transverse momentum field has only a 2nd order term.

$P_{q,\mathrm{perp}}$ in terms of δ and **v**

$$(2\pi)^3 P_{q_\perp}(\mathbf{k_1})\delta_D(\mathbf{k_1}+\mathbf{k_2}) = \langle \tilde{\mathbf{q}}_\perp(\mathbf{k_1})\tilde{\mathbf{q}}_\perp(\mathbf{k_2})\rangle$$

$$= \left\langle \int \frac{d^3k'}{(2\pi)^3} \tilde{\mathbf{v}}_\perp(\mathbf{k}')\delta(\mathbf{k_1}-\mathbf{k}') \cdot \int \frac{d^3k'}{(2\pi)^3} \tilde{\mathbf{v}}_\perp(\mathbf{k}')\delta(\mathbf{k_2}-\mathbf{k}') \right\rangle$$

$$P_{q_\perp} = \sum_{i=1}^{3} \left[1-(\hat{k}^i)^2\right] P_q^{ii}$$

where

$$(2\pi)^3 P_q^{ij}(k)\delta_D(\mathbf{k_1}+\mathbf{k_2})$$

$$= \int \frac{d^3k'}{(2\pi)^3} \int \frac{d^3k''}{(2\pi)^3} \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^i(\mathbf{k}')\tilde{v}^j(\mathbf{k}'') \right\rangle$$

$P_{q,perp}$ in terms of δ and **v**

Using Wick's theorem
(<ABCD> = <AB><CD> + <AC><BD> + <AD><BC>),
the 4th order bracket can be decomposed into pair brackets.

$$
\begin{aligned}
&\left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^i(\mathbf{k}')\tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^j(\mathbf{k}'') \right\rangle \\
&= \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^i(\mathbf{k}') \right\rangle \left\langle \tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^j(\mathbf{k}'') \right\rangle \\
&+ \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{\delta}(\mathbf{k_2}-\mathbf{k}'') \right\rangle \left\langle \tilde{v}^i(\mathbf{k}')\tilde{v}^j(\mathbf{k}'') \right\rangle \\
&+ \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^j(\mathbf{k}'') \right\rangle \left\langle \tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^i(\mathbf{k}') \right\rangle
\end{aligned}
$$

$P_{q,perp}$ in terms of δ and **v**

$$\left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^i(\mathbf{k}')\tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^j(\mathbf{k}'')\right\rangle$$

$$= \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^i(\mathbf{k}')\right\rangle\left\langle \tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^j(\mathbf{k}'')\right\rangle$$

$$+ \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\right\rangle \left\langle \tilde{v}^i(\mathbf{k}')\tilde{v}^j(\mathbf{k}'')\right\rangle$$

$$+ \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^j(\mathbf{k}'')\right\rangle \left\langle \tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^i(\mathbf{k}')\right\rangle$$

$$P_{q_\perp} = \int \frac{d^3k'}{(2\pi)^3}\left(1-\mu'^2\right)$$

$$\left[P_{\delta\delta}(|\mathbf{k}-\mathbf{k}'|)P_{vv}(\mathbf{k}') - \frac{k'}{|\mathbf{k}-\mathbf{k}'|}P_{\delta v}(|\mathbf{k}-\mathbf{k}'|)P_{\delta v}(\mathbf{k}')\right]$$

$(\mu' \equiv \hat{k}\cdot\hat{k}')$

(Ma & Fry 2002)

$P_{q,perp}$ in terms of δ and **v**

$$P_{q_\perp} = \int \frac{d^3k'}{(2\pi)^3}\left(1-{\mu'}^2\right)$$

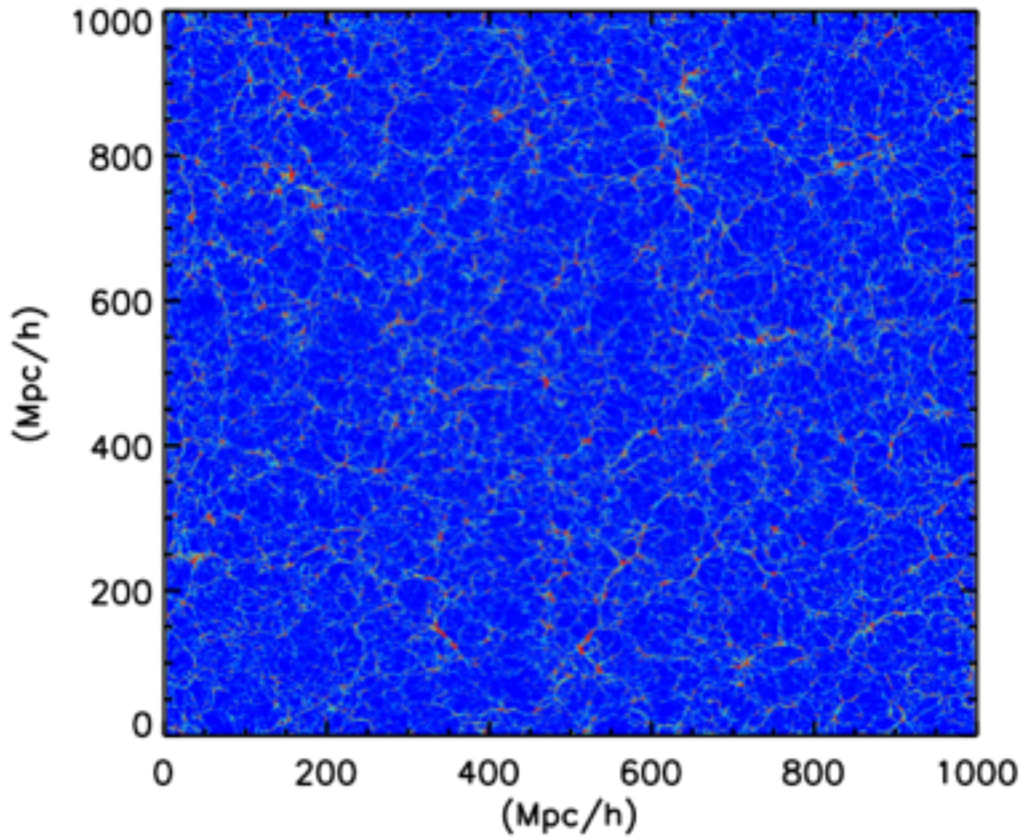
$$\left[P_{\delta\delta}(|\mathbf{k}-\mathbf{k}'|)P_{vv}(\mathbf{k}') - \frac{k'}{|\mathbf{k}-\mathbf{k}'|}P_{\delta v}(|\mathbf{k}-\mathbf{k}'|)P_{\delta v}(\mathbf{k}')\right]$$

$(\mu' \equiv \hat{k}\cdot\hat{k}')$

(Ma & Fry 2002)

Does this expression really hold in the nonlinear regime?

Testing the analytic expression of $P_{q,perp}$



Code : CubeP3M

Size : 1 Gpc/h

# of ptls : 3456^3

We use *N*-body simulation data to test the non-linear expression

$P_{q,perp}$ in terms of δ and **v**

$$P_{q_\perp} = \int \frac{d^3k'}{(2\pi)^3}\left(1-{\mu'}^2\right)$$
$$\left[P_{\delta\delta}(|\mathbf{k}-\mathbf{k}'|)P_{vv}(\mathbf{k}') - \frac{k'}{|\mathbf{k}-\mathbf{k}'|}P_{\delta v}(|\mathbf{k}-\mathbf{k}'|)P_{\delta v}(\mathbf{k}')\right]$$
$$(\mu' \equiv \hat{k}\cdot\hat{k}')$$

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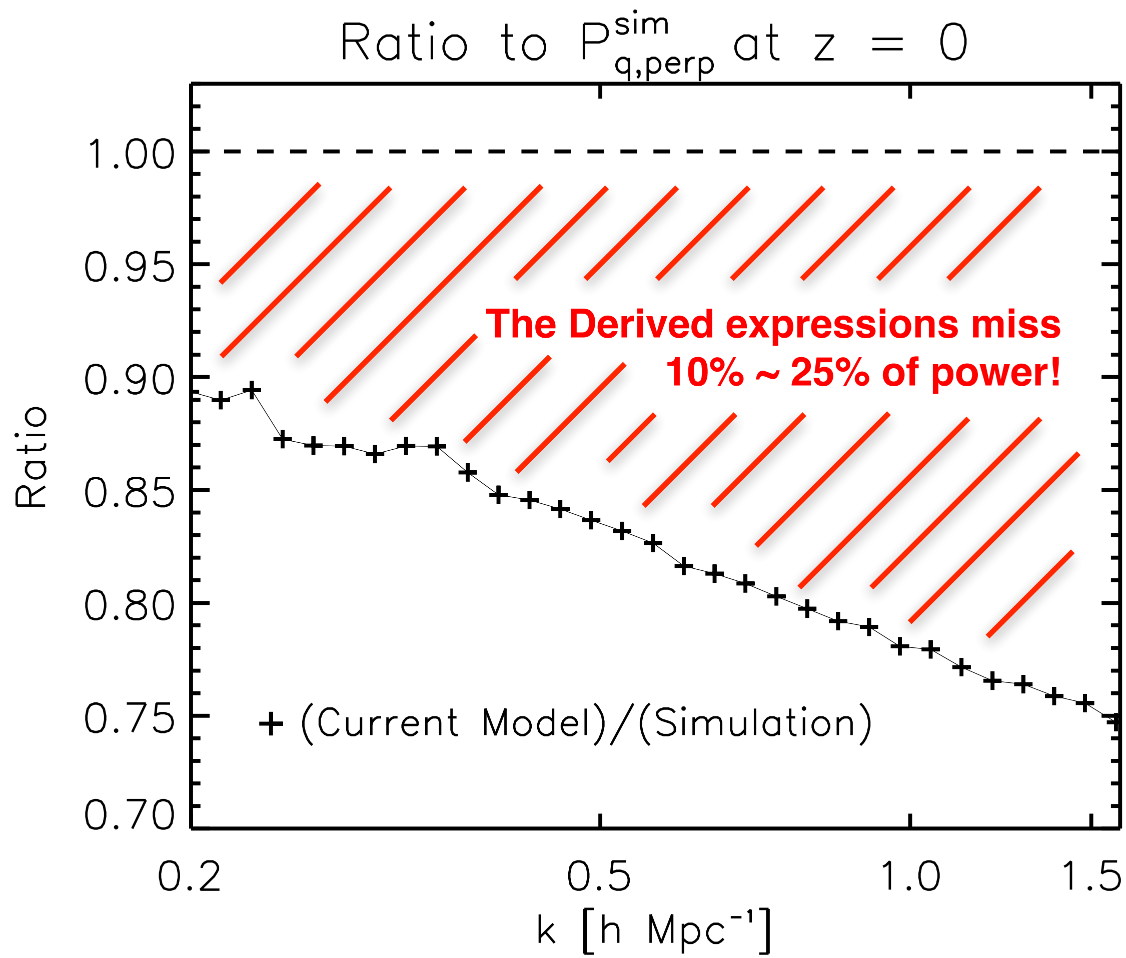
Testing the analytic expression of $P_{q,perp}$



(Park et al. 2016)

What is wrong with the analytic expression?

Wick's theorem works only for gaussian fields. In the nonlinear regime where density and velocity becomes non-gaussian, we need a correction term called "Connected Moment".

$$\left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^i(\mathbf{k}')\tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^j(\mathbf{k}'') \right\rangle$$

$$= \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^i(\mathbf{k}') \right\rangle \left\langle \tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^j(\mathbf{k}'') \right\rangle$$

$$+ \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{\delta}(\mathbf{k_2}-\mathbf{k}'') \right\rangle \langle \tilde{v}^i(\mathbf{k}')\tilde{v}^j(\mathbf{k}'') \rangle$$

$$+ \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^j(\mathbf{k}'') \right\rangle \left\langle \tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^i(\mathbf{k}') \right\rangle$$

$$+(\text{Connected Moment})$$

Perturbation Theory Expansion

$$\delta = \delta^{(1)} + \delta^{(2)} + \ldots$$

$$\delta^{(2)}(\mathbf{k}) = \int \frac{d^3k_a}{(2\pi)^3} \int d^3k_b \; \delta^{(1)}(\mathbf{k_a})\delta^{(1)}(\mathbf{k_b})F_2(\mathbf{k_a},\mathbf{k_b})\delta_D(\mathbf{k}-\mathbf{k_a}-\mathbf{k_b})$$

$$F_2(\mathbf{q_1},\mathbf{q_2}) = \frac{5}{7} + \frac{1}{2}\frac{\mathbf{q_1}\cdot\mathbf{q_2}}{q_1 q_2} + \frac{2}{7}\left(\frac{\mathbf{q_1}\cdot\mathbf{q_2}}{q_1 q_2}\right)^2$$

$$\theta \equiv \nabla\cdot\mathbf{v} = \theta^{(1)} + \theta^{(2)} + \ldots$$

$$\theta^{(2)}(\mathbf{k}) = -\int \frac{d^3k_a}{(2\pi)^3} \int d^3k_b \; \delta^{(1)}(\mathbf{k_a})\delta^{(1)}(\mathbf{k_b})G_2(\mathbf{k_a},\mathbf{k_b})\delta_D(\mathbf{k}-\mathbf{k_a}-\mathbf{k_b})$$

$$G_2(\mathbf{q_1},\mathbf{q_2}) = \frac{3}{7} + \frac{1}{2}\frac{\mathbf{q_1}\cdot\mathbf{q_2}}{q_1 q_2} + \frac{4}{7}\left(\frac{\mathbf{q_1}\cdot\mathbf{q_2}}{q_1 q_2}\right)^2$$

Nonlinear terms can be expressed in terms of linear terms using perturbation theory

What is wrong with the analytic expression?

$$
\begin{aligned}
&\left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^i(\mathbf{k}')\tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^j(\mathbf{k}'')\right\rangle \\
&= \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^i(\mathbf{k}')\right\rangle \left\langle \tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^j(\mathbf{k}'')\right\rangle \\
&+ \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\right\rangle \left\langle \tilde{v}^i(\mathbf{k}')\tilde{v}^j(\mathbf{k}'')\right\rangle \\
&+ \left\langle \tilde{\delta}(\mathbf{k_1}-\mathbf{k}')\tilde{v}^j(\mathbf{k}'')\right\rangle \left\langle \tilde{\delta}(\mathbf{k_2}-\mathbf{k}'')\tilde{v}^i(\mathbf{k}')\right\rangle \\
&+ (\text{Connected Moment})
\end{aligned}
$$

Connected Moment of $P_{q,perp}$ Next-to-leading order

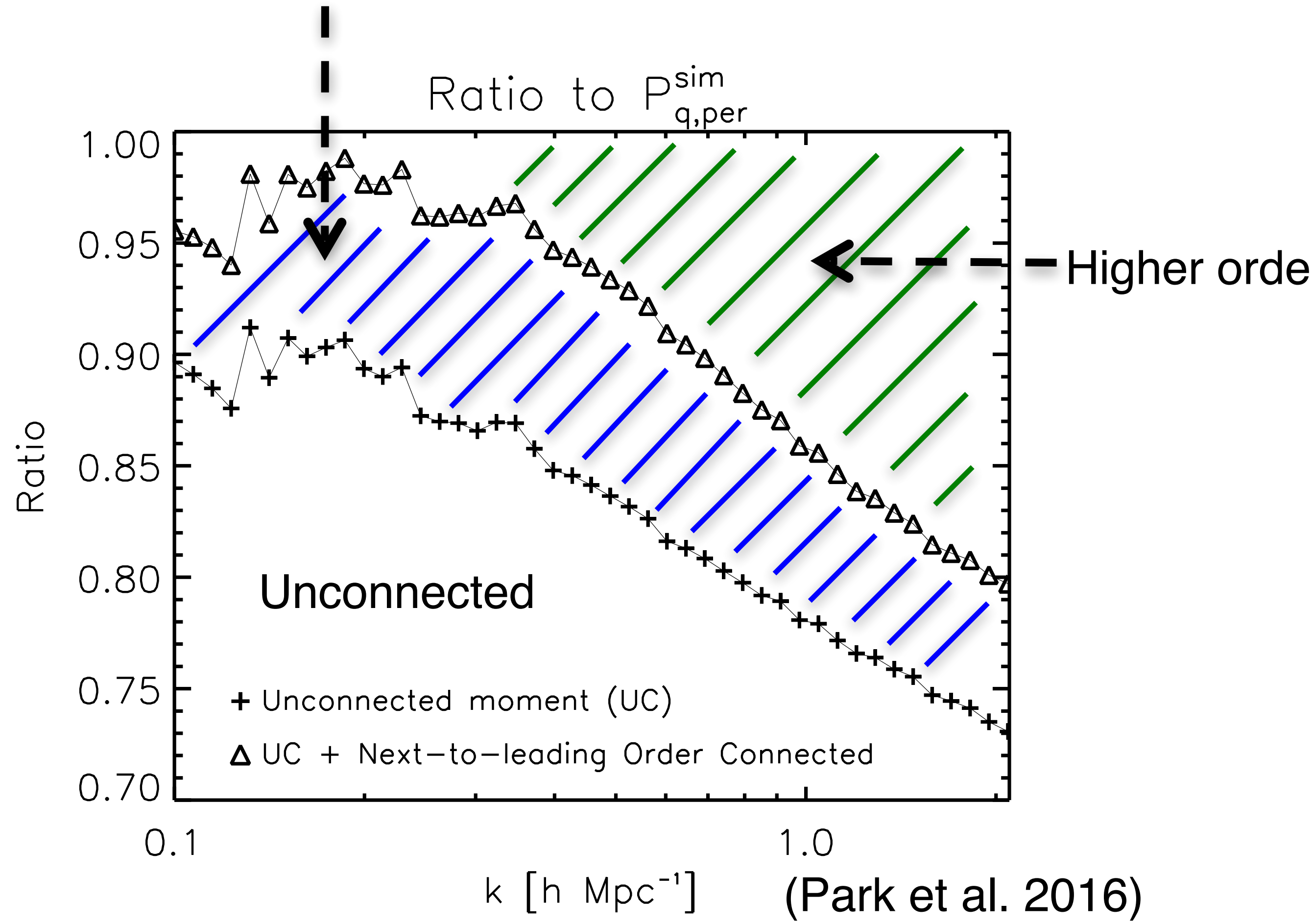
$$
\begin{aligned}
P_{q_\perp,c} = & -\int \frac{d^3k'}{(2\pi)^3}\int \frac{d^3k''}{(2\pi)^3}\left[\frac{1-(\hat{\mathbf{k}}\cdot\hat{\mathbf{k}}')(\hat{\mathbf{k}}\cdot\hat{\mathbf{k}}'')}{k'k''}\right] \\
& [6[F_3^{(s)}(\mathbf{k}+\mathbf{k}'',-\mathbf{k}',-\mathbf{k}'')P(\mathbf{k}+\mathbf{k}'')P(\mathbf{k}')P(\mathbf{k}'') \\
& +F_3^{(s)}(\mathbf{k}-\mathbf{k}',\mathbf{k}',\mathbf{k}'')P(\mathbf{k}-\mathbf{k}')P(\mathbf{k}')P(\mathbf{k}'') \\
& +G_3^{(s)}(\mathbf{k}-\mathbf{k}',-\mathbf{k}-\mathbf{k}'',\mathbf{k}'')P(\mathbf{k}-\mathbf{k}')P(\mathbf{k}+\mathbf{k}'')P(\mathbf{k}'') \\
& +G_3^{(s)}(\mathbf{k}-\mathbf{k}',-\mathbf{k}-\mathbf{k}'',\mathbf{k}')P(\mathbf{k}-\mathbf{k}')P(\mathbf{k}+\mathbf{k}'')P(\mathbf{k}')] \\
& +4[F_2^{(s)}(\mathbf{k}-\mathbf{k}',\mathbf{k}'+\mathbf{k}'')G_2^{(s)}(\mathbf{k}'+\mathbf{k}'',-\mathbf{k}'')P(\mathbf{k}-\mathbf{k}')P(\mathbf{k}'+\mathbf{k}'')P(\mathbf{k}'') \\
& +F_2^{(s)}(\mathbf{k}-\mathbf{k}',\mathbf{k}'+\mathbf{k}'')G_2^{(s)}(-\mathbf{k}'-\mathbf{k}'',\mathbf{k}')P(\mathbf{k}-\mathbf{k}')P(\mathbf{k}'+\mathbf{k}'')P(\mathbf{k}') \\
& +G_2^{(s)}(\mathbf{k},-\mathbf{k}+\mathbf{k}')F_2^{(s)}(\mathbf{k},\mathbf{k}'')P(\mathbf{k}-\mathbf{k}')P(\mathbf{k})P(\mathbf{k}'') \\
& +G_2^{(s)}(\mathbf{k},-\mathbf{k}+\mathbf{k}')G_2^{(s)}(\mathbf{k},-\mathbf{k}-\mathbf{k}'')P(\mathbf{k}-\mathbf{k}')P(\mathbf{k})P(\mathbf{k}+\mathbf{k}'') \\
& +G_2^{(s)}(\mathbf{k}-\mathbf{k}'+\mathbf{k}'',-\mathbf{k}+\mathbf{k}')F_2^{(s)}(\mathbf{k}-\mathbf{k}'+\mathbf{k}'',\mathbf{k}')P(\mathbf{k}-\mathbf{k}')P(\mathbf{k}-\mathbf{k}'+\mathbf{k}'')P(\mathbf{k}') \\
& +G_2^{(s)}(\mathbf{k}-\mathbf{k}'+\mathbf{k}'',-\mathbf{k}+\mathbf{k}')G_2^{(s)}(\mathbf{k}-\mathbf{k}'+\mathbf{k}'',-\mathbf{k}-\mathbf{k}'')P(\mathbf{k}-\mathbf{k}')P(\mathbf{k}-\mathbf{k}'+\mathbf{k}'')P(\mathbf{k}+\mathbf{k}'') \\
& +F_2^{(s)}(-\mathbf{k}'-\mathbf{k}'',\mathbf{k}+\mathbf{k}'')G_2^{(s)}(-\mathbf{k}'-\mathbf{k}'',\mathbf{k}'')P(\mathbf{k}+\mathbf{k}'')P(\mathbf{k}'+\mathbf{k}'')P(\mathbf{k}'') \\
& +F_2^{(s)}(-\mathbf{k}'-\mathbf{k}'',\mathbf{k}+\mathbf{k}'')G_2^{(s)}(-\mathbf{k}'-\mathbf{k}'',\mathbf{k}')P(\mathbf{k}+\mathbf{k}'')P(\mathbf{k}'+\mathbf{k}'')P(\mathbf{k}') \\
& +G_2^{(s)}(-\mathbf{k}-\mathbf{k}''+\mathbf{k}',\mathbf{k}+\mathbf{k}'')F_2^{(s)}(-\mathbf{k}-\mathbf{k}''+\mathbf{k}',\mathbf{k}'')P(\mathbf{k}+\mathbf{k}'')P(\mathbf{k}-\mathbf{k}'+\mathbf{k}'')P(\mathbf{k}'') \\
& +G_2^{(s)}(-\mathbf{k},\mathbf{k}+\mathbf{k}'')F_2^{(s)}(-\mathbf{k},\mathbf{k}')P(\mathbf{k}+\mathbf{k}'')P(\mathbf{k})P(\mathbf{k}') \\
& +F_2^{(s)}(\mathbf{k},-\mathbf{k}')F_2^{(s)}(\mathbf{k},\mathbf{k}'')P(\mathbf{k})P(\mathbf{k}')P(\mathbf{k}'') \\
& +F_2^{(s)}(\mathbf{k}-\mathbf{k}'+\mathbf{k}'',\mathbf{k}')F_2^{(s)}(\mathbf{k}-\mathbf{k}'+\mathbf{k}'',-\mathbf{k}'')P(\mathbf{k}')P(\mathbf{k}-\mathbf{k}'+\mathbf{k}'')P(\mathbf{k}'')]]
\end{aligned}
$$

We have derived the connected term in the next-to-leading order.

(Park et al. 2016)

Connected Moment of $P_{q,perp}$

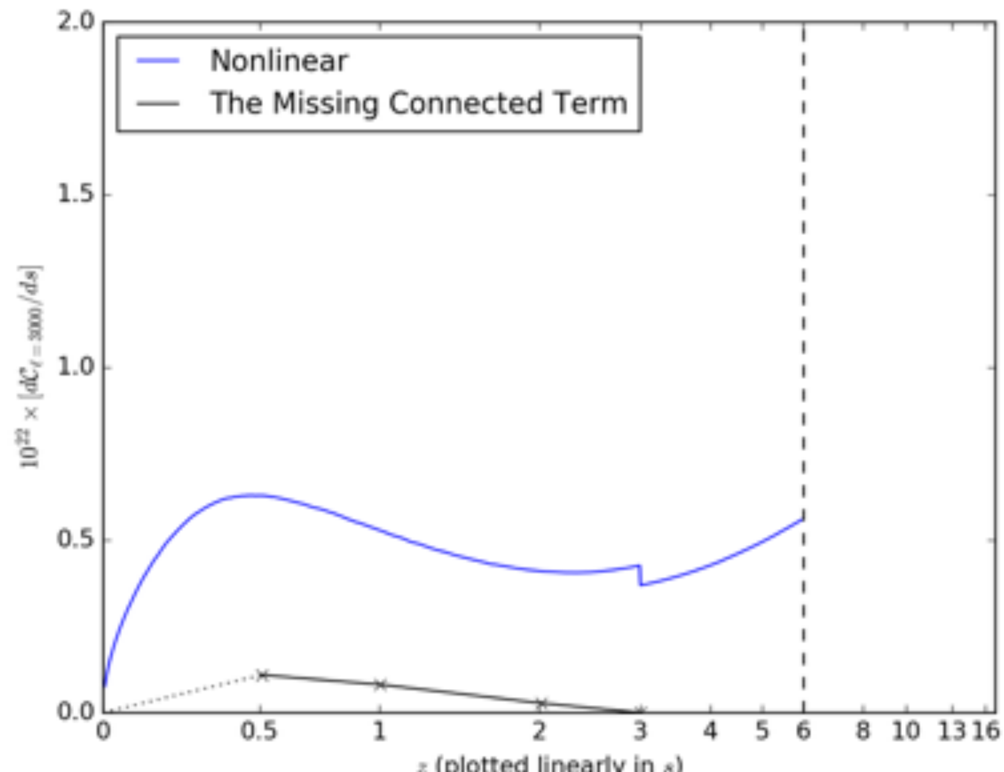
Next-to-leading order



(Park et al. 2016)

Next-to-leading order explains the deficit up to k ~ 0.3 *h*/Mpc !
At k > 0.3 h/Mpc, perhaps higher-order terms dominates.

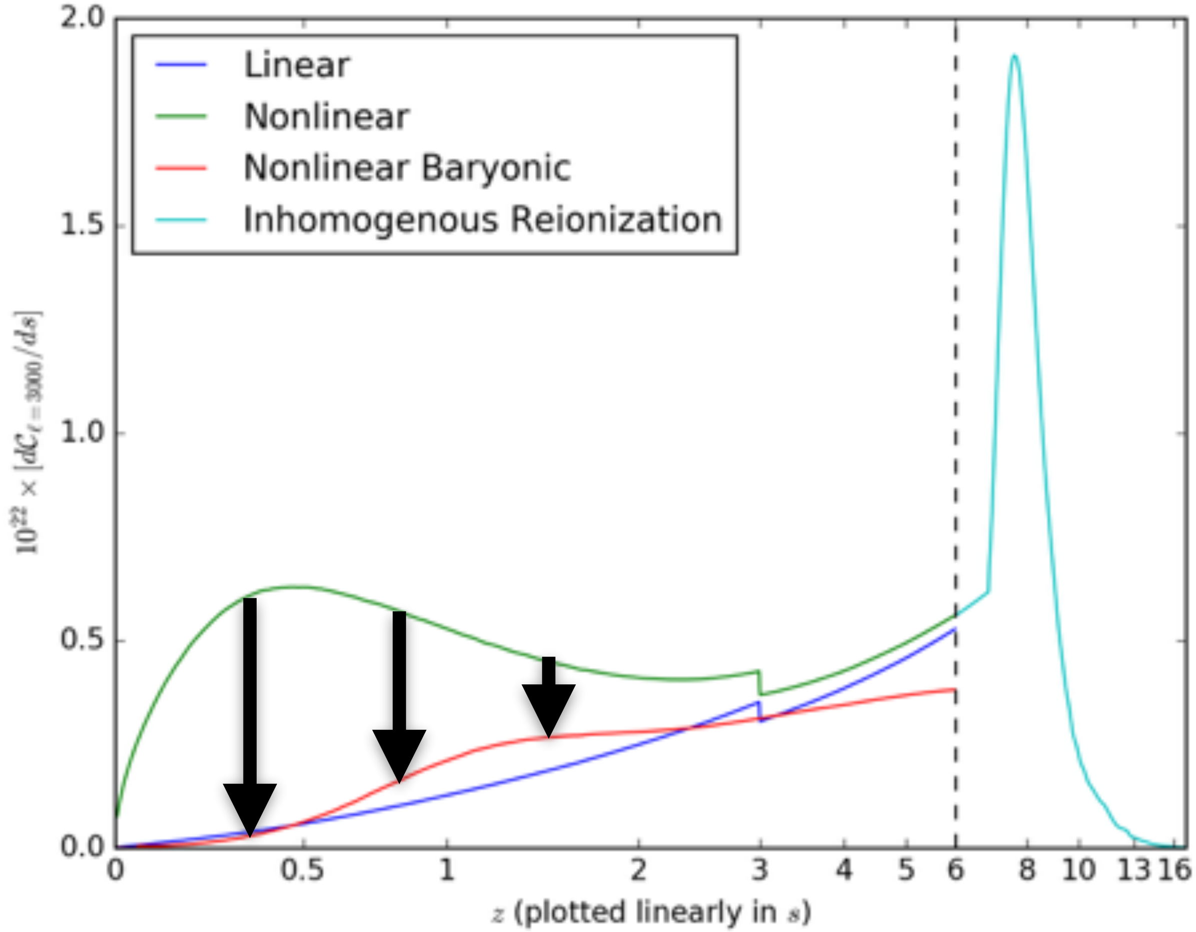
Final Result of Part 2



(Park et al. 2016)

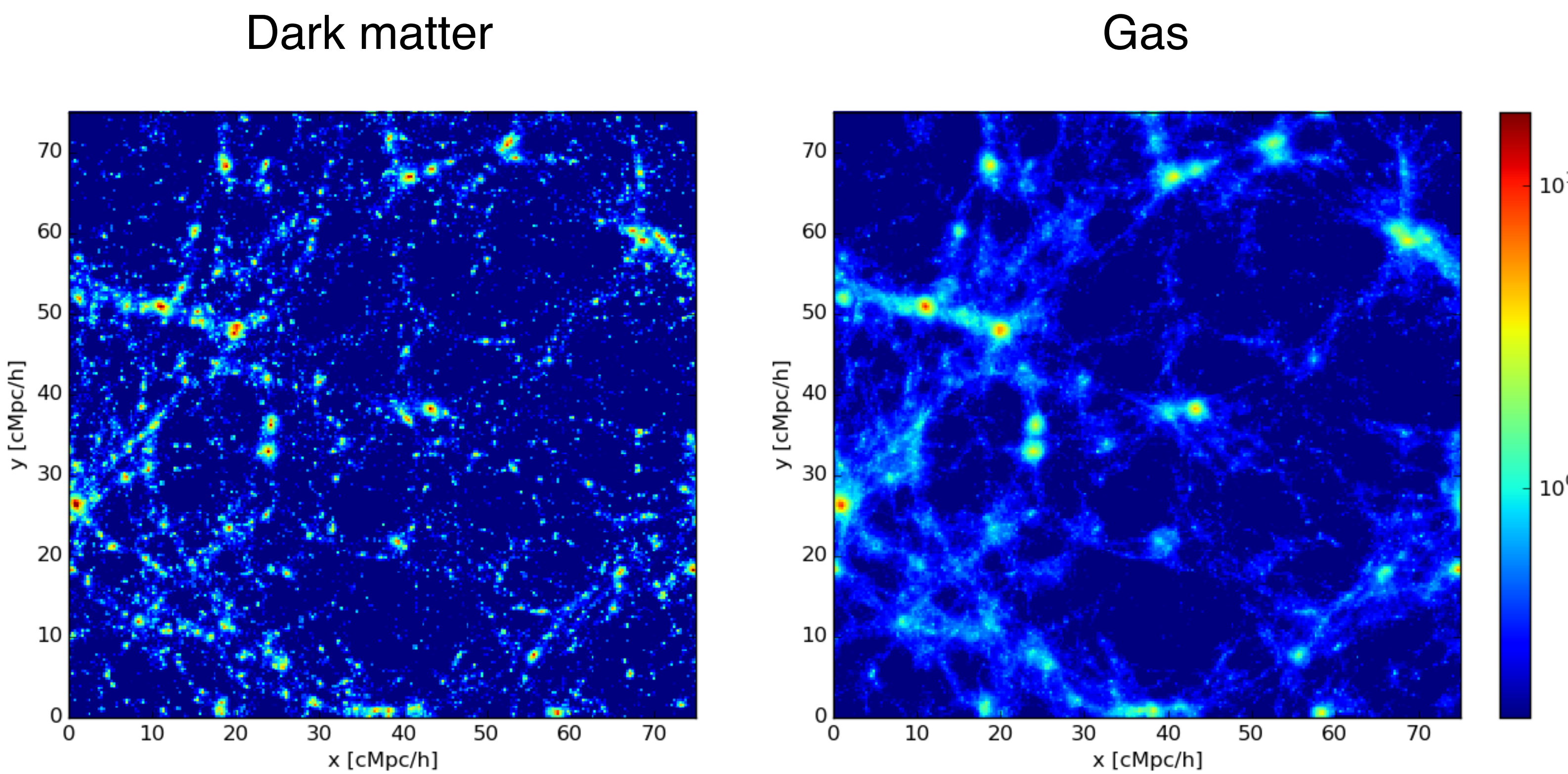
The connected term add ~10% extra to the kSZ signal compared to the previous expression that missed the connected term.

Part 3) Effect of Baryonic Physics in the kSZ signal



At low redshift, offset between dark matter and gas due to baryonic physics becomes a significant effect.

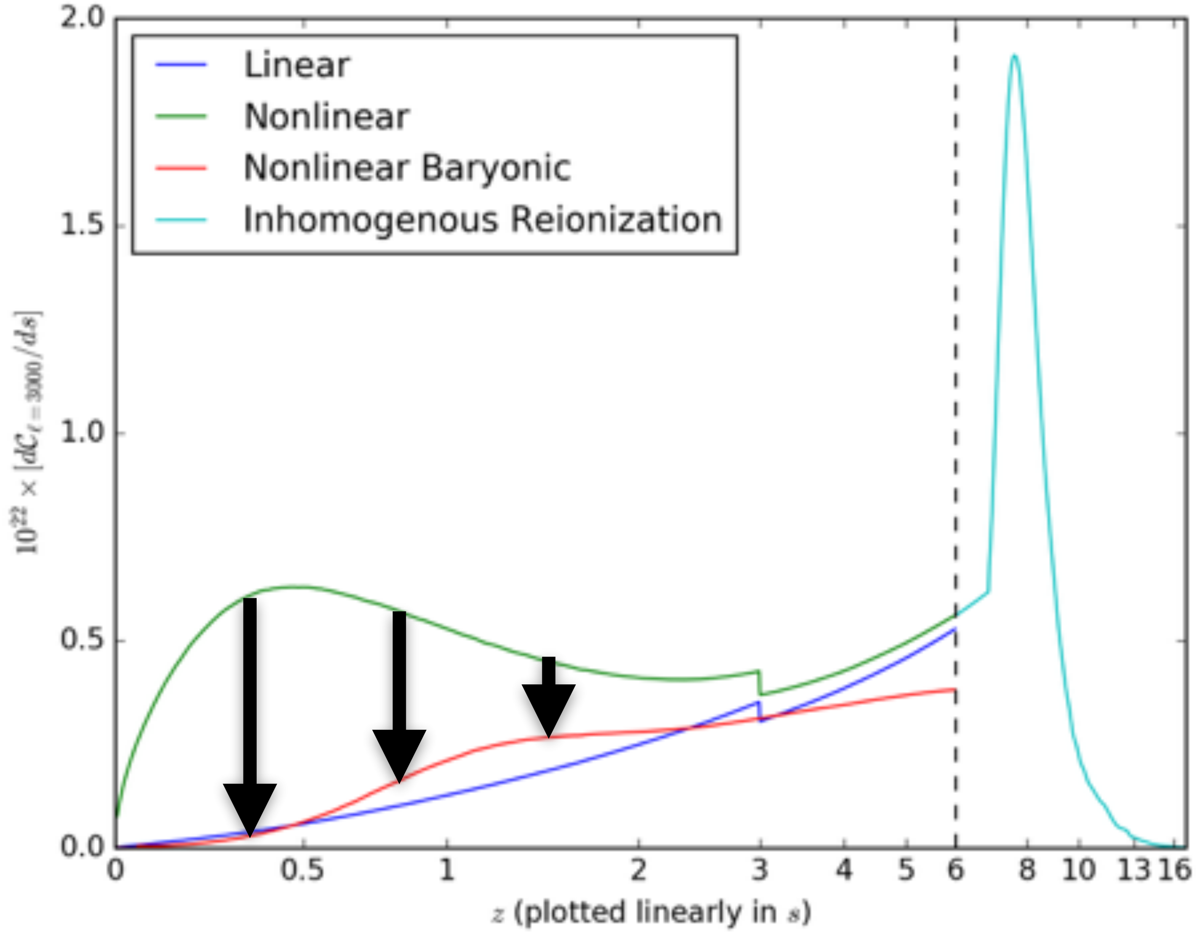
Part 3) Impact of Baryonic Physics in the kSZ signal



There are two things happening to the baryonic density field in low z

1) **Pressure in gas wipes out density structures.**
2) **Star formation locks some gas into stars.**

Part 3) Effect of Baryonic Physics in the kSZ signal



Both effects act toward suppressing the signal.

How to model the baryonic effect in the kSZ signal

The first step is to use the baryonic density power spectrum in the equation below.

$$P_{q_\perp} = \int \frac{d^3k'}{(2\pi)^3}\left(1-\mu'^2\right)$$

$$\left[P_{\delta\delta}(|\mathbf{k}-\mathbf{k}'|)P_{vv}(\mathbf{k}') - \frac{k'}{|\mathbf{k}-\mathbf{k}'|}P_{\delta v}(|\mathbf{k}-\mathbf{k}'|)P_{\delta v}(\mathbf{k}')\right]$$

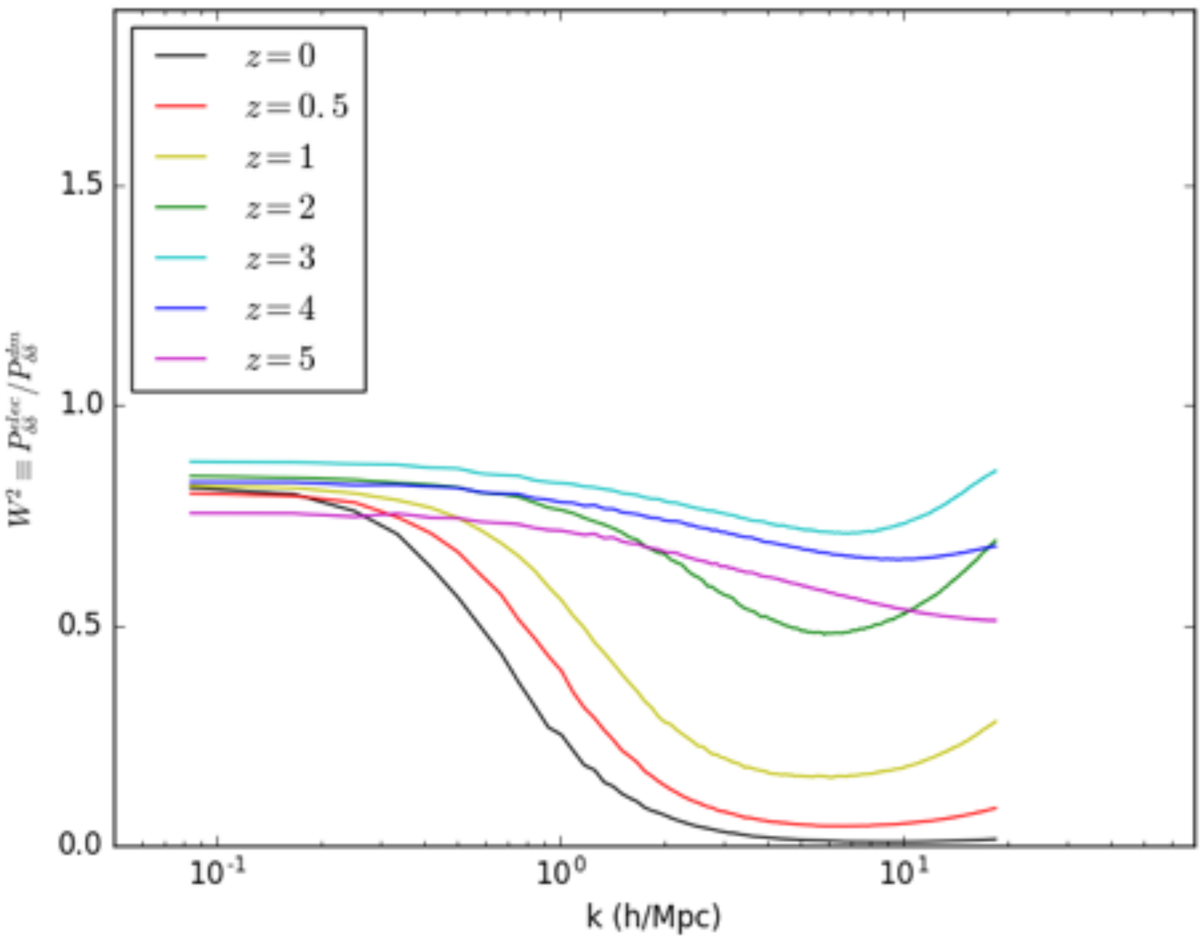
Assume the baryonic density field is related to the dark matter density field by a window function, *W*.

$$\tilde{\delta}_b(k) = W(k)\tilde{\delta}_{dm}(k) \quad \longrightarrow \quad \begin{aligned} P^b_{\delta\delta}(k) &= W^2(k)P^{dm}_{\delta\delta}(k) \\ P^b_{\delta v}(k) &= W(k)P^{dm}_{\delta v}(k) \end{aligned}$$

Illustris Simulation

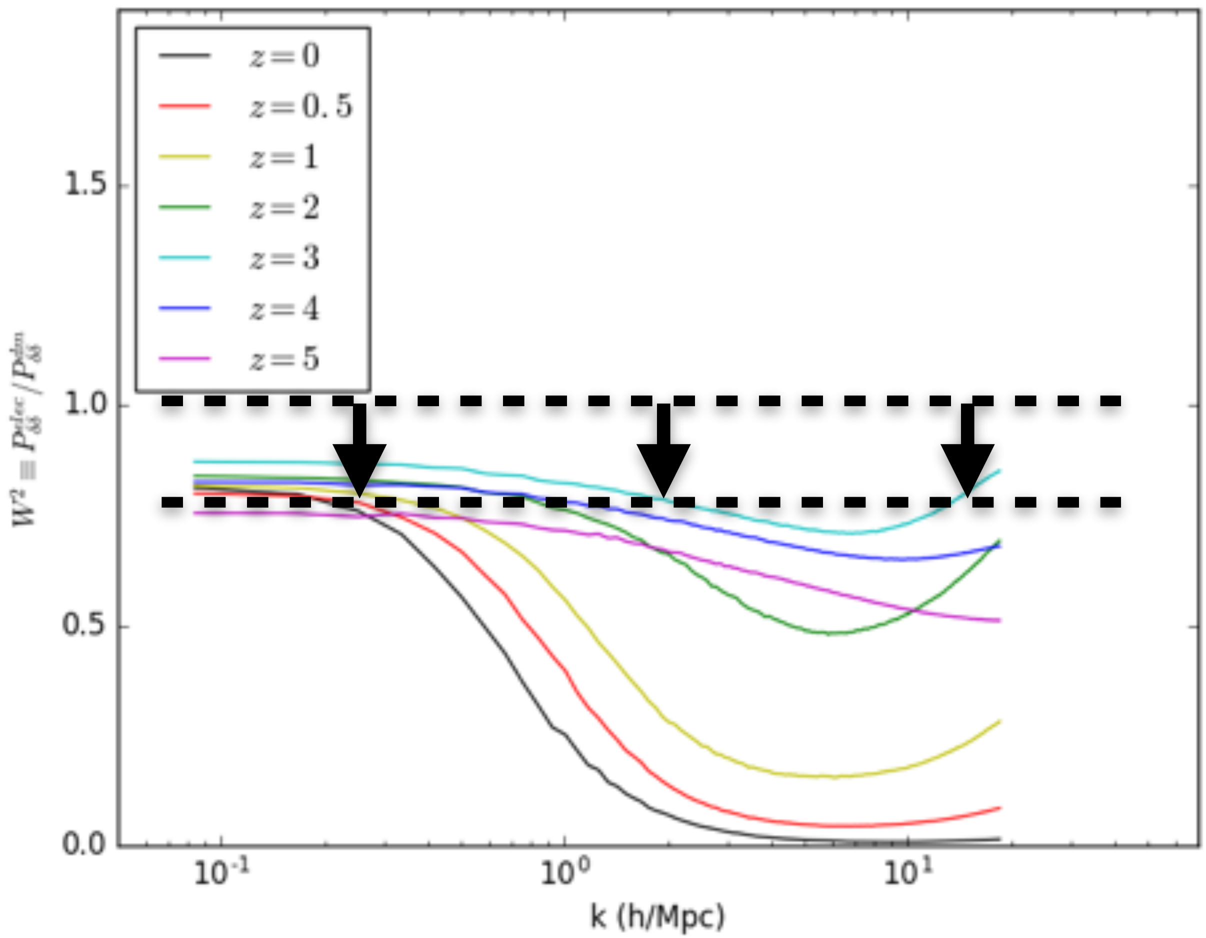
Illustris simulation has a fairly large size (75 Mpc/*h*) with baryonic physics included.

Window function from Illustris



(Park et al. in prep.)

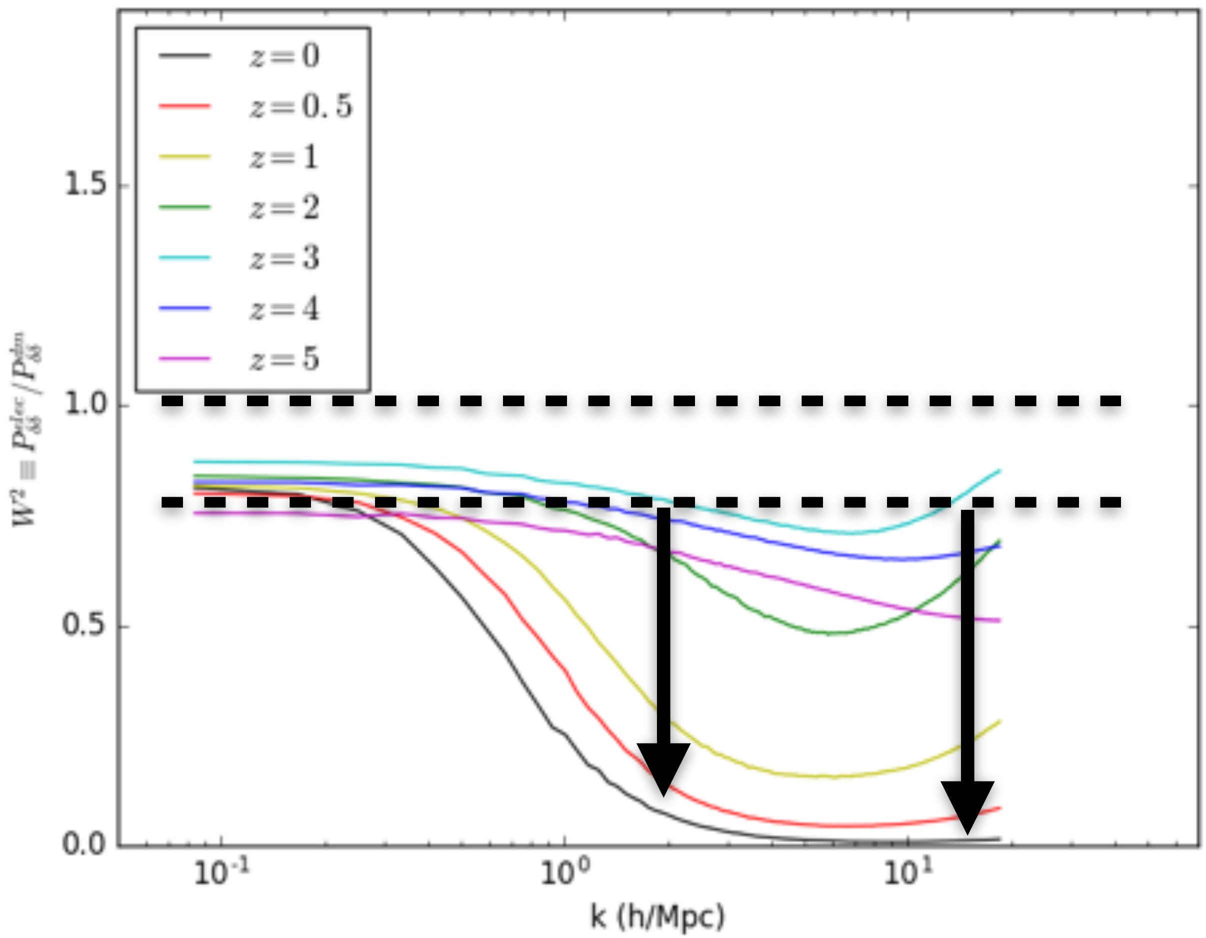
Window function from Illustris



Suppression at all scales due to gas locked into stellar products.

(Park et al. in prep.)

Window function from Illustris

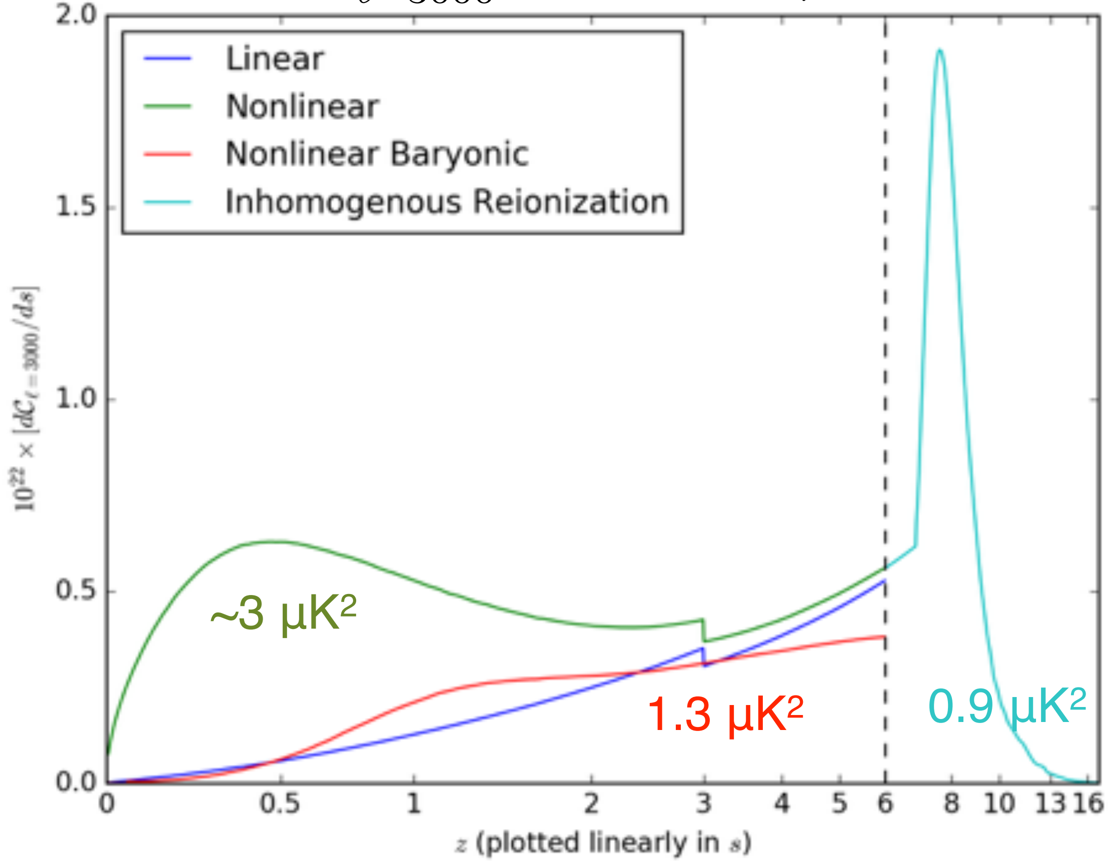


Extra suppression at small-scales and low-redshift due to pressure.

(Park et al. in prep.)

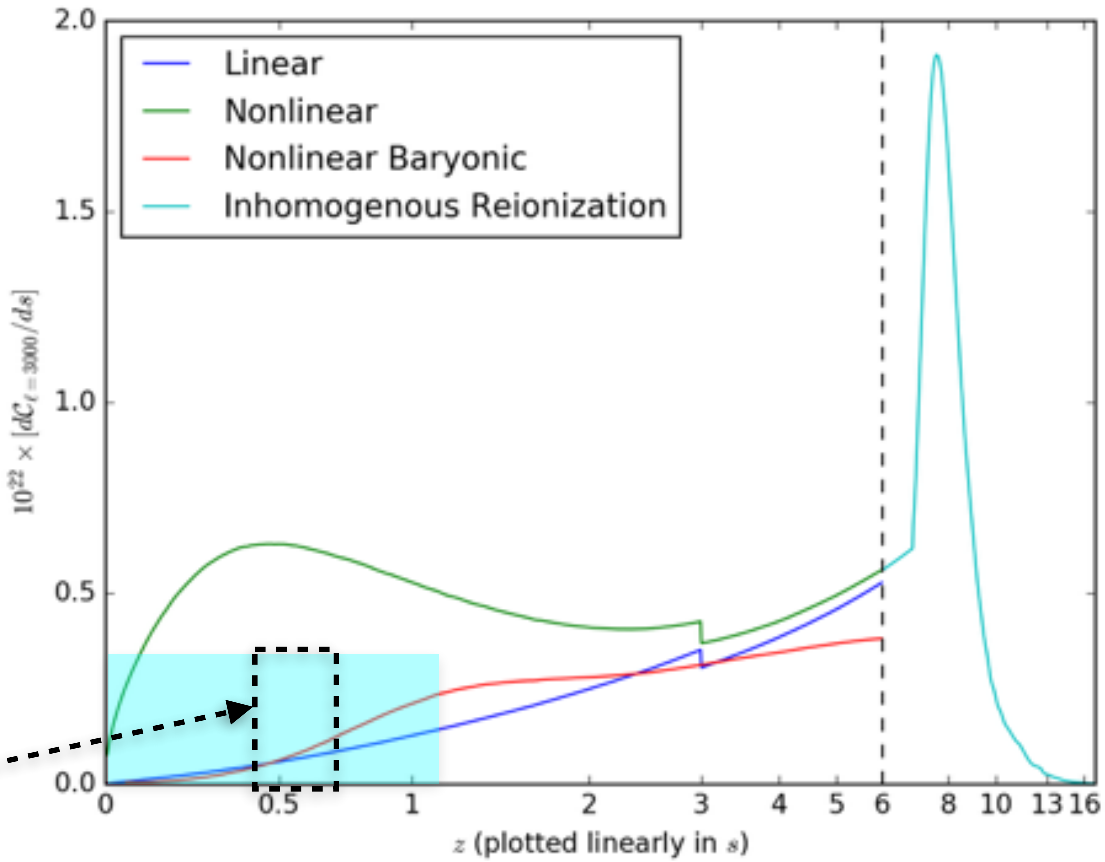
Result for Part 3
Post-reionization kSZ signal

$$\mathcal{D}_{\ell=3000}^{\rm SPT} = 2.9 \pm 1.3 \ \mu K^2$$



We find 1.3 μK² for the post-reionization signal accounting for both the effects of nonlinear growth of structures and baryonic physics. (Park et al. in prep.)

What We Can Learn From Large-scale Structure Surveys



Analyzed by Schann et al 2015 using BOSS data & ACTPol

Measuring LSS and its correlation with CMB should help constraining the kSZ signal from post-reionization Era too.

Summary

- The impact of low-mass galaxies are not distinguishable in the kSZ signal at $l = 3000$ where we can currently observe, but it will be at $l = 10000$.
- There is a missing term in the expression for $P_{q,perp}$ from previous literature. That term adds ~10% extra to the post-reionization signal.
- Using Illustris simulation we model the baryonic effect in the post-reionization ($z < 6$) kSZ signal and include it in the calculation. The result is $D_{l=3000} = 1.3\ \mu K^2$.
- Observation of LSS should confirm theoretical prediction and help constraining the post-reionization signal.